# Dynamic Behavior of Copper and Other Metals at Extreme Loading Rates

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Our objective has been to develop a theory that predicts the behavior of metals subjected to extreme loading rates. The analysis is placed at the mesoscale of the material and is elevated into the scale of continuum. The theory is used in direct numerical simulations and guides the development of predictive constitutive equations for copper, tin, and other metals.

Metals subjected to extreme loading rates exhibit behavior that is characteristic of a thermodynamically open system characterized by exchanging energy due to dislocations traveling long distances with a nearly sonic velocity. The thermodynamic openness is rarely observed in solids; therefore the mean-field theories of nonlinear continuum dynamics often provide sufficient representation of the solid behavior. These theories describe the deformation and damage processes with the use of constitutive models. In addition, an equation of state (EOS) that couples high hydrostatic pressure and changes in mass density and temperature is formulated. Difficulties arise when a metal is subjected to extreme loading. Then, the material experiences a mesoscale excitation coupled with velocity fluctuations and a non-negligible entrapment of kinetic energy.

Our dynamic defect structure (DDS) model described in [1, 2] predicts that various metals (alloys) subjected to extreme loading rates experience a strong mesoscale excitation leading to an entrapment of kinetic energy. While a significant portion of the energy is converted into heat, the remaining part supports a rearrangement of the material's internal structure and causes fluctuations in the field of velocity, strains, and stresses. The DDS theory explains a remarkable increase in the plastic hardening rate [3, 4] observed in copper, iron, nickel, aluminum, and ES steel at strain rates greater than $10^3$ $s^{-1}$. Furthermore, DDS confirms findings in [5] that metals subjected to extreme loading rates dissipate energy that is much greater than predicted by the classic thermodynamic calculations. Finally, DDS links the development of the dynamic dislocation structures with the mesoscale entrapment of kinetic energy; both the events promote heterogeneous phase transformation and melting. The behavior has already been observed in tantalum subjected to the pressure of 6 GPa [6], where line visar measurements confirm a highly perturbed profile of free surface

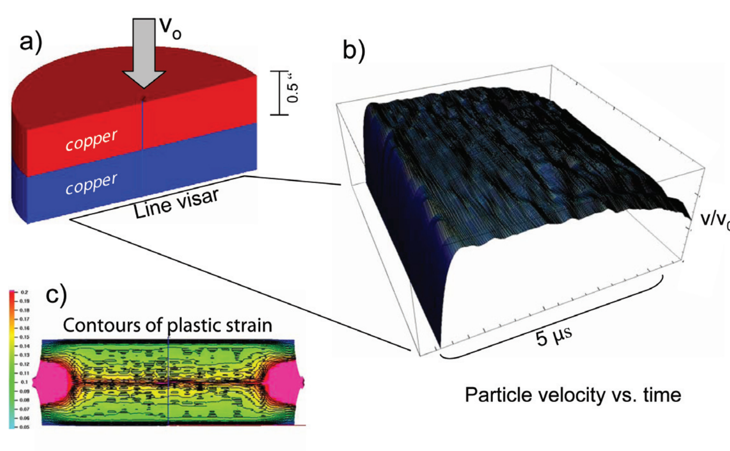


*Fig. 1.*
*Dynamic behavior of a copper plate subjected to impact loading: a) Cu/Cu plate impact, b) free surface velocity as a function of time, and c) contours of plastic strain.*

velocity. As shown in Fig. 1, the DDS theory is very successful in predicting this behavior. Findings of the theory help in constructing predictive constitutive equations for various metals. For example, the behavior of copper [7] is predicted in a broad range of strain rates ($10^{-3}$ to $2 \times 10^3$/s) and temperatures (298 to 1173 K), Figs. 2a and 2b. At strain rates greater than $10^3$/s, the theory describes an abrupt increase in the plastic hardening rate (flow stress at strains equal to 15, 30, and 60%), Fig. 2c. The behavior matches well with the experimental data presented in [4]. As shown in Fig. 2d, the strong increase in the flow stress competes with the process of dynamic recovery which results from an increase of temperature caused by adiabatic heating. At strain rates greater than $10^5$/s, the flow stress still increases but with a much slower rate. This type of behavior has already been observed in [6], where high pressure (HP) and oxygen-free electronic (OFE) copper subjected to a strong shocks (57 and 77 GPa) experience dynamic recovery and recrystallization.

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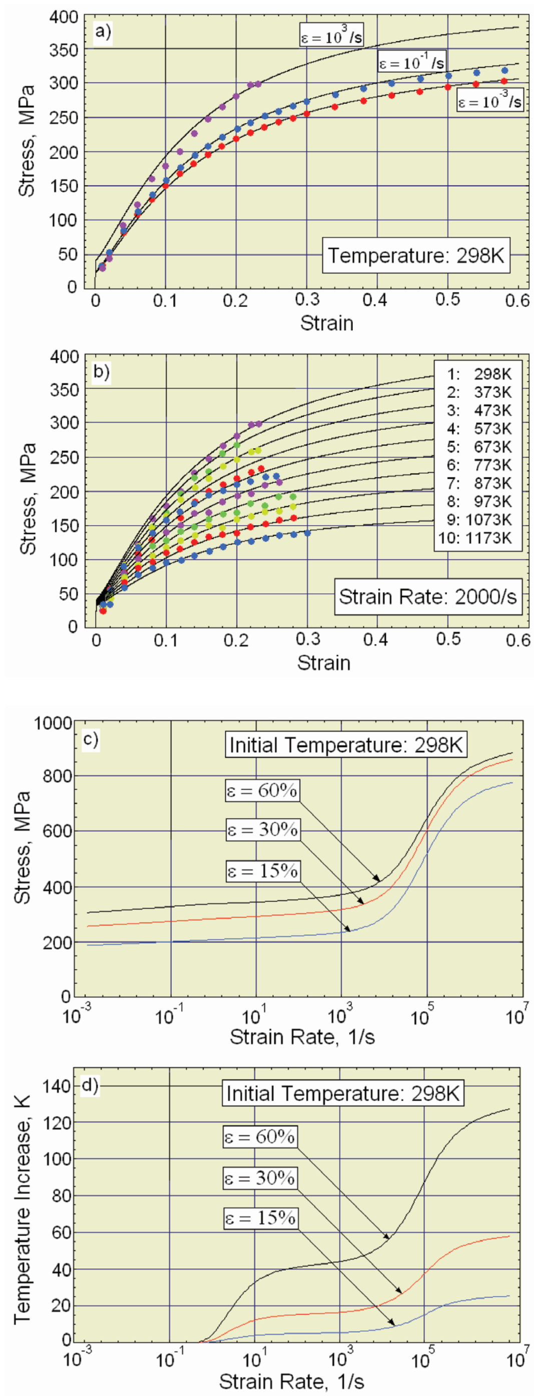


*Fig. 2.*
***Predicted behavior of copper: a) stress/strain responses of copper at various strain rates and room temperature; b) stress/strain responses for various temperatures at high strain rate; c) flow stress at strains equal to 15, 30, and 60% versus strain rates; and d) temperature increase due to adiabatic heating at strains 15, 30, and 60%.***

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